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# VOLTAGE AND CURRENT MONITOR FOR SCIENTIFIC SATELLITES

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FOR SCIENTIFIC SATELLITES

## LIST OF ILLUSTRATIONS




It is with sincere appreciation that I acknowledge the contributions of Dr. William A. Geyger for his technical advice in the early design stage of this monitoring circuit. I would like also to thank Dr. Robert W. Rochelle, Roland L. Van Allen, and Stephen Paull for their time and help in editing this report. Also I would like to thank Walter Kofahl who gave so freely of his time while this circuit was being balanced and under-going environmental testing.

# VOLTAGE AND CURRENT MONITOR FOR SCIENTIFIC SATELLITES

## INTRODUCTION

This paper gives a detailed description of a voltage and current monitor applicable to spacecraft technology comprised of a self-balancing magnetic-amplifier circuit using d. c. bias. This circuit is capable of monitoring voltages of full-scale ranges from 1 to 3000 volts and currents ranged from 1 milli-ampere to greater than 10 amperes with an accuracy of $\pm 0.5\%$. The power consumed may vary from less than one milliwatt to approximately eight milliwatts depending upon the load required. In spacecraft applications the telemetry system may present a load varying, 1,000 ohms to 20,000 ohms and under these conditions the power consumed by the monitor circuit is in the order of eight milliwatts.

In spacecraft applications it is desirable to monitor several potentials such as the main-voltage converter potential, the transmitter potential and other vital spacecraft potentials that may be of interest. These potentials may vary in magnitude from a few volts to one hundred volts depending upon the size and mission of the spacecraft.

The spacecraft currents to be monitored may vary from a small trickle charge of a few milliamperes to the solar array current or the spacecraft main bus current. These currents can be in the order of five amperes.

There are many techniques available to the design engineer to perform the above task. For example, the voltage monitor could be a simple voltage divider circuit, and the current monitor could be a Hall-Effect generator or a saturable reactor. None of these however, are adequate to cover the wide dynamic ranges encountered with good linearity. A technique that can fulfil this requirement is the self-balancing magnetic-amplifier. This circuit is capable of accepting a d. c. or a. c. voltage or current signal over a wide dynamic range and producing a d. c. voltage at its output proportional to the input with an accuracy of $\pm 0.5\%$. Furthermore, when the d. c. output voltage is connected to an analog oscillator in the spacecraft telemetry, a frequency is produced which is directly proportional to this voltage. This frequency is telemetered to a satellite tracking station and stored on tapes. With the aid of a voltage vs. frequency calibration curve the magnitude of the spacecraft voltage or current being monitored can be determined.

## CIRCUIT OPERATION

The self balancing magnetic amplifier circuit is shown in Figure 1. An advantage of using this type of circuit is the tendency to minimize:

(1) The variation in the rectifier reverse characteristics.

(2) The effects of supply voltage variations.

(3) The effects of frequency variations.

The operation of this circuit is such that when the voltage $E_p$ goes positive, core 1 is driven into positive saturation through load winding $N_L$ and at the same time core 2 is driven into negative saturation through winding $N_L'$. This situation is reversed when voltage $E_p$ goes negative. The effect of any discrepancy in the two core characteristics will tend to be reduced to a minimum. The bias current $I_b$ supplied from the power supply $E_{p1}$ through $R_B$ and $R_2$ resistors is directly proportional to the voltage $E_{p1}$. The quiescent current $I_Q$ is that current which will flow in the output load windings $N_L$ and $N_L'$ when the control current flowing through control windings $N_c$ equals zero. This quiescent current $I_Q$ is controlled by the bias current flowing in the bias windings $N_B$ and $N_B'$. These windings act as additional control windings to make the quiescent current $I_Q$ practically independent over a voltage supply $E_{p1}$ variation from $\pm 5$ to $\pm 10$ percent.

## CIRCUIT DESIGN

In designing magnetic amplifier circuits, three problems confront the design engineer: (1) Design of the magnetic amplifier, (2) Design of the load into which the magnetic amplifier is to operate, and (3) Design of the power supply necessary to drive the magnetic amplifier.

1. Magnetic Amplifier.

Many factors enter into the selection of the proper magnetic amplifier circuits. Some of these are covered in references (1) and (2). When the magnetic amplifier is employed as a d-c instrument and the time of response is not a major problem, one may choose a magnetic amplifier of the self-balancing type with d-c bias. The reasons for this selection are as follows:

a) An advantage of this circuit is that with properly applied d-c bias; the quiescent current can be made substantially independent of any changes in the supply voltage $E_p$; and

b) The quiescent current can be decreased to a few micro-amperes. These become important factors when currents in the order of a few milliamperes are to be monitored.

a. Operating Point. In order to reduce quiescent current, we must consider the fact that the Law of Equal Ampere Turns only holds over a portion of its range. The transformer turns-ratio may be expressed as

$$\frac{I_L}{I_c} = \frac{N_C}{N_L} \tag{1}$$

then

$$I_L N_L = f\ (I_c N_c) \tag{2}$$

where

$I_L$ = current in the load winding

$N_L$ = the number of turns in the load winding

$I_c$ = current in the control winding

$N_c$ = number of turns in the control winding

A plot of equation (2) is shown in Figure 2. Point B' determines the quiescent current ($I_Q$) in the load windings when current in the control windings is reduced to zero. It is this $I_Q$ that causes trouble when low currents are to be monitored. W. Kramer, Ref. 5, has shown that, by adjusting the bias, point B' can be reduced to zero. To illustrate this, consider point B in figure 2 as the quiescent operating point. If a negative d-c bias is applied this point moves to point A' which results in a much smaller quiescent current $I_Q$. As can be seen from figure 2, Equation (2) is not linear near A', and therefore the circuit has very low sensitivity in this region. This nonlinearity becomes a very important problem when currents of a few tenths of a milliampere are to be monitored.

When the current to be monitored is 100 milliamperes or more, however the nonlinearity at point A' is so minute that for all practical applications it can be ignored. The quiescent operating point in this particular situation may be determined as follows:

(1) Resistors of bias windings ($N_B$) equal approximately 500 ohms each.

(2) The bias resistor ($R_b$) is 75,000 ohms.

(3) Bias voltage ($N_B$) equals 9 volts d. c.

This gives a required bias current $I_b$ of 0.1 ma which is well below any value of current this circuit is required to monitor. Figure 2 has been expanded in the region of A' for clarity.

b. Magnetic Cores. Reference 1 shows that 78% nickel - 22% iron tape-wound core material is required for good operation in magnetic amplifiers with a power supply of 15 to 20 volts. This material has low magnetizing current and consumes less power than the 50% nickel-50% iron type, and was therefore selected for the current and voltage monitor circuit. Operating parameters for the transformers were selected as follows:

(1) A quiescent current of 0.1 to 0.2 milliamperes as calculated in the previous section.

(2) Expected loud impedance of 10 to 20 kilo-ohms.

(3) Power supply voltage $E_p$ = 18 volts to insure that cores are fully saturated and constant output voltage with a possible $\pm 5\%$ variation in supply voltage.

c. Windings. In selecting the number of turns for the bias and load windings, the following factors must be considered:

(1) The minimum current to be measured by the monitoring circuit.

(2) The power supply voltage selected.

(3) Core material used.

The minimum current to be measured by the monitoring circuit is important because it determines the lowest possible $I_Q$. One way to achieve low $I_Q$ is to make $N_L$ and $N_b$ as large as possible. With a given volume for the monitoring circuit, the best way to achieve this is to select a core with a small cross-sectional area and a large inside diameter. This will result in large windings. The dimensions of the core may be obtained from a manufacturer's specification sheet. Maximum possible number of turns is given by the expression

$$N = \frac{W}{KA_W} \tag{3}$$

where

$W$ = core window area, in $cm^2$,

$A_W$ = wire cross-section area including insulation, in $cm^2$, and

$K$ = a winding factor determined by the characteristics of the coil winding facilities.

When currents of 1 to 10 amperes are to be monitored, a control winding of 1 turn is sufficient, and we may set $N_L$ and $N_b$ equal to $N/_2$. For monitoring lower currents, a good practise is to make $N_c + N_b = N_L$. The size of $N_c$ varies inversely with the current to be monitored as shown in Table 1.

TABLE 1

| No. turns of $N_c$ | Current Range Amperes |
|---|---|
| 1 | $1 \longrightarrow 10$ |
| 20 | .5 |
| 100 | .1 |
| 400 | .025 |
| 2000 | .005 |
| 10,000 | .001 |

d. Voltage Monitoring Operation. The design for low current monitoring will apply to voltage monitoring applications, that is, $N_c$ will equal $N_b$, and $N_c + N_b = N_L$. For our particular application, $N_c$ and $N_b$ will equal to 1750 turns each, and $N_L$ will equal 3500 turns. The resistance of the winding $N_c$ is approximately equal to 250 ohms. Now suppose the magnetic amplifier is balanced in such a way as to have a voltage gain of unity, that is $E_L/E_c = 1$ where $E_L$ = output voltage and $E_c$ = voltage to be monitored. In this case, if 5 volts is applied to the control winding $N_c$, 5 volts will be produced across the load resistor. Now, suppose we want this magnetic amplifier to monitor a 25-volt source and still have an output voltage of 5 volts. The procedure is as follows:

(1) With $E_c$ set at 5 volts, observe that the current in the control winding $N_c$ is

$$I_c = \frac{5}{250} = 20 \text{ ma} \tag{4}$$

(2) With $E_c$ equal to 25 volts, place a resistor $R_c$ in series with the control winding such that

$$R_c = \frac{25}{20} \times 10^3 = 1250 \text{ ohms} \tag{5}$$

With this series resistor, the magnetic amplifier is capable of reading voltages up to 25 volts. This range can be extended to monitor voltages as high at 10, 000 volts providing the proper size core, windings, and series resistor are chosen.

2. Load.

When a magnetic amplifier is employed as a d-c instrument, it is important to have the load current $I_L$ correspond to the input signal current of the magnetic-amplifier circuit. One such circuit could take the form of a simple voltage mixing circuit as shown in Figures 3. $R_1$ $R_2$ are connected across the load winding of Core 1 and Core 2. The two voltages $E_1$ and $E_2$ represent the rectified voltage appearing across these windings when Cores 1 and 2 are conducting respectively. The average voltage across $R_L$ is equal to the difference between $E_1$ and $E_2$. When these two outputs are equal, the total voltage applied to the load resistor is zero.

The bias applied to the magnetic amplifier is such that the total m. m. f. controlling Core 1 is equal:

$$I_b N_b = I_c N_c \tag{6}$$

and that controlling Core 2 is

$$I_b N_b = -I_c N_c \tag{7}$$

Thus, if the control current is increased from zero, the control ampere-turns on Core 1 increase while those on Core 2 decrease. If the control current is decreased, the effect is reversed.

The analysis of Figure 3 is governed by the amount of bias applied to the magnetic amplifier circuit. A full analytical treatment of this subject may be found in Reference 6.

3. Power Supply.

To produce the driving voltage and frequency necessary to supply the magnetic amplifier, a dc-to-ac converter using transistor switching and a square-loop magnetic core was used. This type of circuitry gives a constant volt-second waveform. A great deal of technical literature describing the design and operation of such circuits has been published, and many elaborate circuits have been built verifying this literature. Basically, all of these circuits can be resolved into the circuit as shown in Figure 4. See Appendix for design equations.

Factors to consider in selecting the magnetic core and transistors are given in the following sections:

a. Magnetic Core:

(1) Core size is an inverse function of operating frequency.

(2) For low power levels and light loads, 78% nickel, 22% iron tape-wound core material should be selected.

b. Transistors:

(1) The reverse collector-to-emitter voltage breakdown should be more than twice $E_1$ (see figure 4).

(2) Cut-off frequency should be at least 10 times the power supply operating frequency.

## DESIGN EXAMPLE

1. <u>Design Procedure.</u>

Suppose it is desired to design a current sensor to meet the following requirements:

(1) Current to be monitored is ($0 \rightarrow 5$) amperes.

(2) A linearity of $\pm 1\%$.

(3) Output impedance 10 K ohms or less.

(4) Output is ($0 \rightarrow 5$) v. d. c.

(5) A 12 v. d. c. source is available.

(6) The current sensor must consume less than 10 milliwatts.

(7) Environmental temperature will vary from $-20^{\circ}C$ to $+60^{\circ}C$.

A self balancing magnetic amplifier will be used to monitor this current. Schematic for the entire voltage and current monitor including power supply is shown in figure 5.

## Step 1. Selecting the Core Material

There are two different types of material to choose from.

(a) 50% nickel, 50% iron

(b) 78% nickel, 22% iron

For low power, small magnetizing current, light loads, and high efficiency the 78% nickel, 22% iron material is a better choice. Tape-wound cores using 1 mil thick tape were chosen. (See section under magnetic core in this report).

## Step 2. Core Size to be Used

There are several factors that influence the core size selection; they are as follows:

(a) The total weight allotted for the magnetic amplifier.

(b) Frequency of operation.

(c) Size wire to be used for each winding.

(d) The smallest current the magnetic amplifier is required to monitor.

For the interplanetary monitoring platform (Explorer 18) power and space were the prime considerations. The smallest current to be monitored was 100 milliamperes, and the largest was 5 amperes. The frequency of operation was chosen to be approximately 1000 cycles per second. From these considerations the core selected had the following dimensions: ID = .625", OD = .750", height = .125", core cross section area = .040 $cm^2$.

Step 3. Selecting the Number of Turns for $N_L$ and $N_B$ Windings

Using equation (3):

$$N = \frac{W}{K A_W}$$

By using tape-wound core catalog for this size core the window area W, and the wire cross section area Aw are given. These dimensions give the designer some idea of the upper limit for N. By using A. W. G Size #39 wire, it was possible to put 7000 turns on this size core. Therefore,

$$N = 7000 \text{ turns},$$

$$N_B + N_L = 7000 \text{ turns},$$

and

$$N_B = N_L = 3500 \text{ turns}$$

From table 1., page 8

$$N_c = 1 \text{ turn}$$

Step 4. D. C. Bias Circuit

From the graph in reference 1, page 67, and using 78% nickel, 22% iron type cores the supply voltage $E_p$ was chosen to be 18 volts. The bias voltage was selected to be approximately one-half of $E_p$, or 9 volts.

The actual magnetization current for this particular design, where the supply voltage $E_p$ is 18 volts and the load resistor is approximately 10 K ohms, is .12 milliampere. From this a value of $R_B$ may be computed.

$$R_B = \frac{9}{.12} \times 10^3 \approx 75 \text{ K ohms}$$

Step 5. Load Circuit

Resistors $R_1$ and $R_2$ form a voltage mixing circuit for the magnetic amplifier. The values of $R_1$ and $R_2$ are selected at approximately 5 K ohms. However more will be said about this in a later section on magnetic amplifier balancing. The .47 $\mu$f capacitor is to reduce the ripple voltage that will appear across the load resistor and this value may be increased or decreased depending upon the amount of ripple voltage allowed in the load.

## Step 6. Power Supply Design (See Appendix)

The power supply circuit is a dc-to-ac converter with the following characteristics:

(1) Input voltage is 12 volts dc.

(2) Frequency of operation 1000 cps.

(3) Core material: 1 mil thick tape, 78% nickel, 22% iron.

(4) Core size: ID = 0.625", OD = 0.750", height = 0.125", core cross section area, 0.040 $cm^2$.

(5) Load current approximately 4 milliamperes.

Now using equation (8)

$$N_1 = \frac{12}{4(7000)\,(.04) \times 1000} \times 10^8 =$$

$$\boxed{N_1 \cong 1080}$$

$N_2$ is chosen such that it will supply one volt to the base of the transistor. Then from equation (10)

$$N_2 = N_1 \frac{1}{E_1}$$

$$N_2 = 1080 \frac{1}{12}$$

$$\boxed{N_2 \cong 100 \text{ turns}}$$

Then $N_3$ is found by the desired output voltage. In our case we have chosen 18 volts; and from equation (11)

$$N_3 = N_1 \frac{E_o}{E_1}$$

$$N_3 = 1080 \frac{18}{12}$$

$$\boxed{N_3 = 1610 \text{ turns}}$$

Then

$$V(N_2) = \frac{N_2}{N_1} E = 1.2 \text{ volts}$$

So $R_1$ and $R_2$ may be found by using equations (13). Thus,

$$R_1 = \frac{1.2}{\frac{1610}{1080} \times \frac{4 \times 10^{-3}}{100}}$$

$$\boxed{R_1 \cong 15 \text{ K}}$$

and $R_2$ becomes

$$R_2 = \frac{(12)^2 \times 100}{.25}$$

$$\boxed{R_2 \cong 66 \text{ K ohms}}$$

2. <u>Balancing Procedure.</u>

A magnetic amplifier of the type described above is balanced when equation (2) $N_L I_L = F(N_c I_c)$ produces a linear curve.

Referring to Figure 5, the balancing procedure is as follows:

(a) Place a 5 ampere d-c current supply across terminals (A) and (B).

(b) Place a 4 place digital voltmeter across terminals (C) and (D).

(c) Replace $R_B$, $R_2$, and $R_1$ with decode resistors.

(d) Set the 5 ampere current supply to zero.

(e) Set $R_1$ and $R_2$ to 5000 ohms and set $R_B$ to 75000 ohms. Increase $R_B$ until the voltage across (C) and (D) is a minimum.

(f) Increase the current across terminals (A) and (B) to 5 amperes. Adjust $R_1$ and $R_2$ until the voltage across (C) and (D) reads 5 volts.

(g) Reduce the current supply to zero and note the zero reading. If the previous zero reading has changed, increase $R_B$ until a minimum voltage appears across (C) and (D).

(h) Again increase the 5 ampere supply to 5 amperes and adjust $R_1$ and $R_2$ until 5 volts is read across (C) and (D).

(i) Reduce the current supply to 4 amperes and note the voltage across (C) and (D). If the digital voltmeter does not read 4 volts adjust $R_1$ and $R_2$ until 4 volts is read on the voltmeter.

(j) Repeat steps (h) and (i) until the error is reduced to a minimum.

(k) When (j) is satisfied the magnetic amplifier is balanced and equation (2) satisfied.

With a little practice this balancing procedure will become routine.

## 3. Environmental Test and Results.

The voltage and current monitoring circuit shown in figure 5 was assembled and exposed to the following tests:

(1) Thermal-vacuum test

(a) 24 hours soak at -30°C and $1 \times 10^{-5}$ mm Hg

(b) 24 hours soak at +70°C and $1 \times 10^{-5}$ mm Hg

(2) Acceleration test

(a) 49.4G thrust load combined with 13.6G radial load due to spin of 206 RPM with radius = 11 1/4"

(3) Vibration

(a) Random all axis 20- 3000 cps 54G

(4) Temperature variation -50°C to +70°C

(5) Magnetic flux radiation with 5 amperes flowing in the control winding $N_c$. The Magnetic flux radiated from this circuit is less than 2 gamma at 18 inches.

Figure 6 shows the results of a temperature variation from -20°C to +60°C, and a supply voltage variation of $\pm 5\%$. It can be seen that temperature and voltage variations have little effect on the current monitoring circuit.

The total power required for the circuit is 18 milliwatts. 10 milliwatts are required for the power supply, and 8 milliwatts for the magnetic amplifier.

Following satisfactory operation during tests, the circuit of Figure 5 was flown on the inter planetary monitoring platform Explorer 18 satellite. This satellite was launched from Cape Kennedy 26 Nov. 1963. A modified version of this circuit will be flown on the United Kingdom Satellite.

## CONCLUSION

The circuit described in this report offers a very good solution for measuring currents and voltages of any magnitude with a high degree of linearity and accuracy. Currents as low as one micro-ampere and voltages as high as ten thousand volts have been measured by this method. (see References 1 and 5). From the quality of data received, to date, from Explorer 18 Satellite, tends to verify this conclusion.

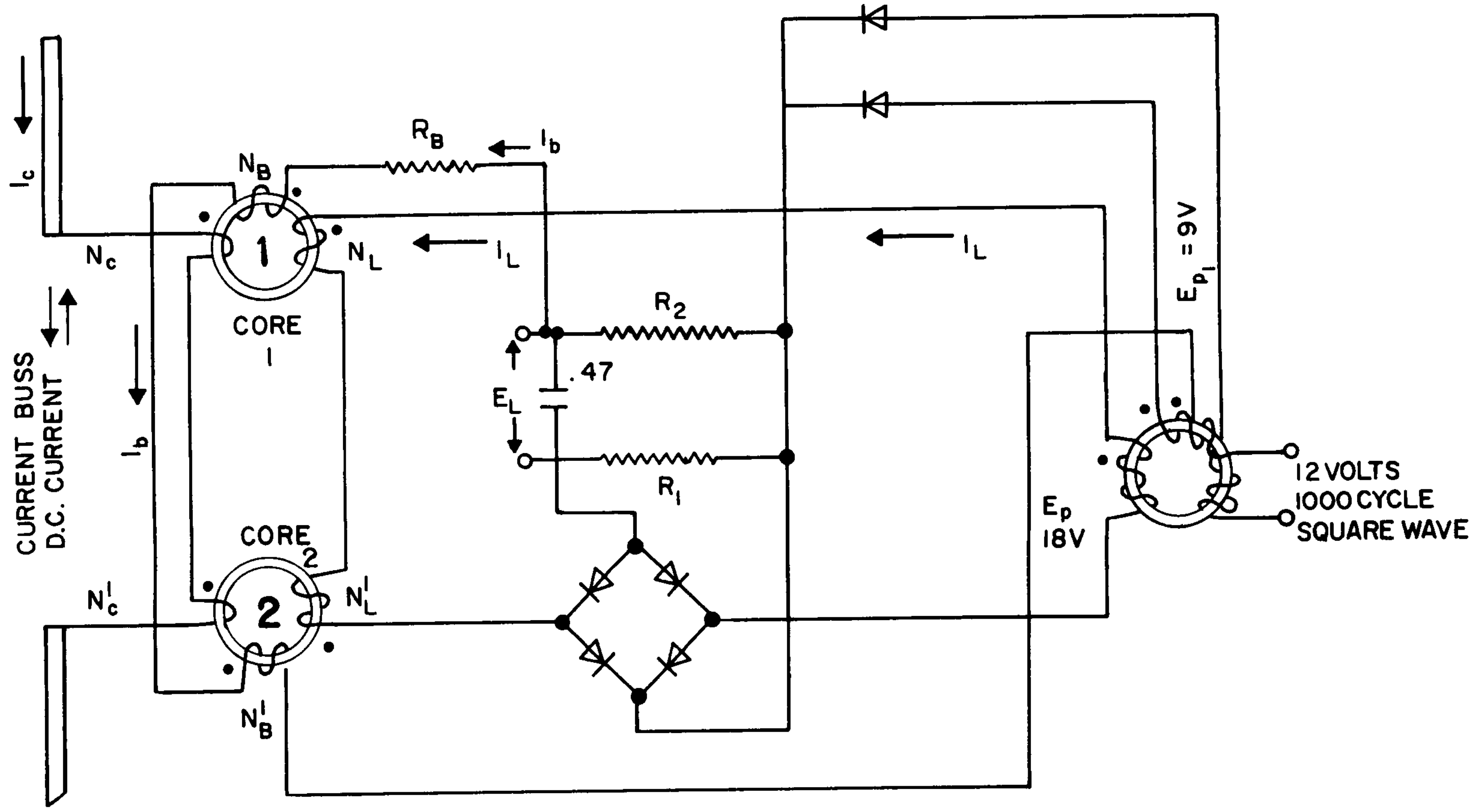
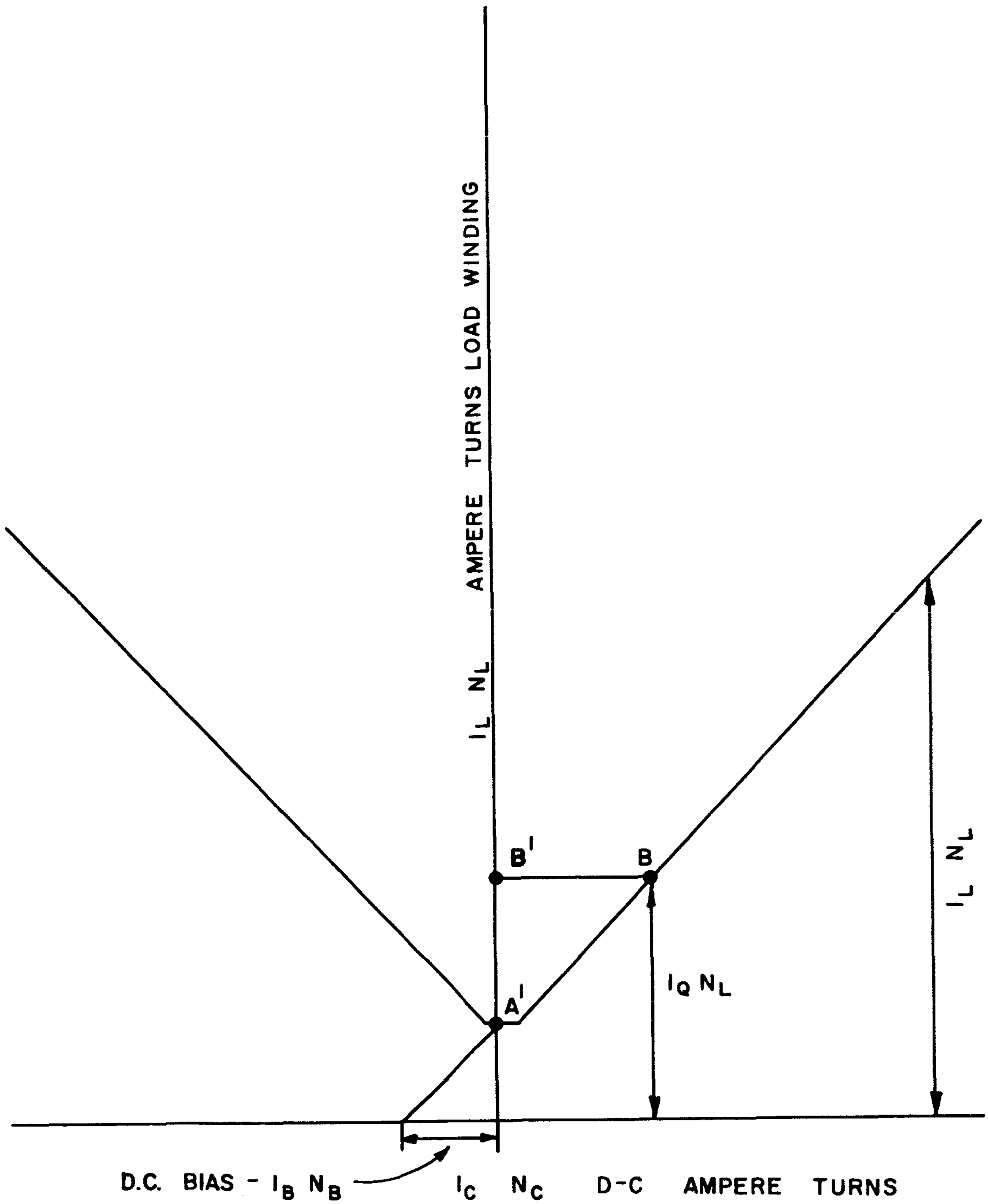



Figure 1. SELF BALANCING MAGNETIC AMPLIFIER CIRCUIT WITH D.C. BIAS




Input vs Output Curve

Figure 2

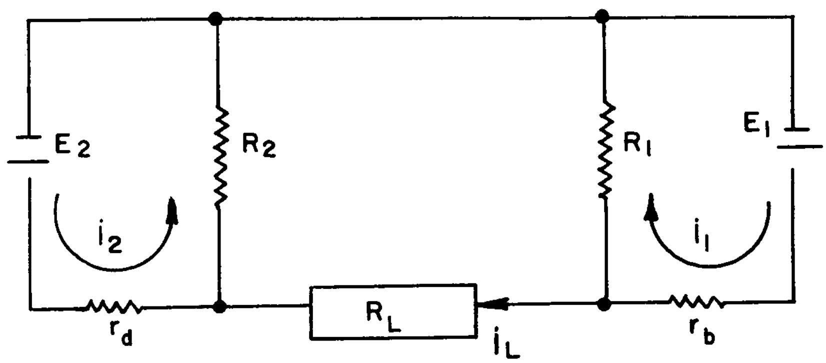



Figure 3. MAGNETIC AMPLIFIER LOAD CIRCUIT

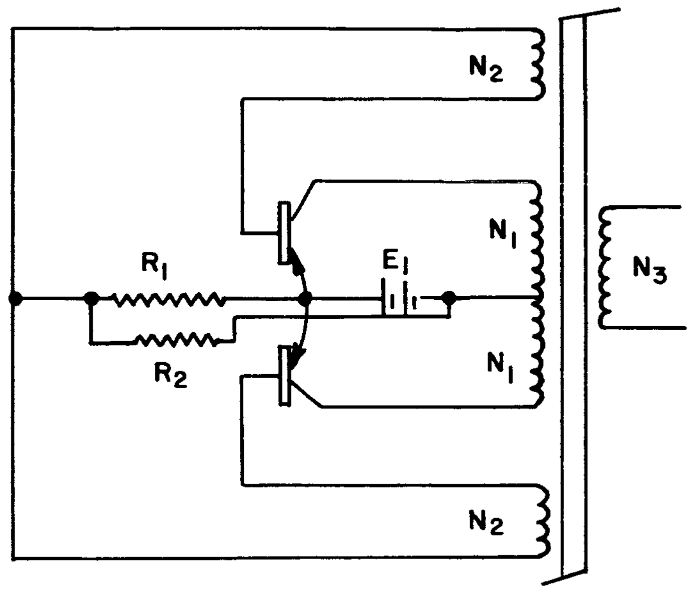
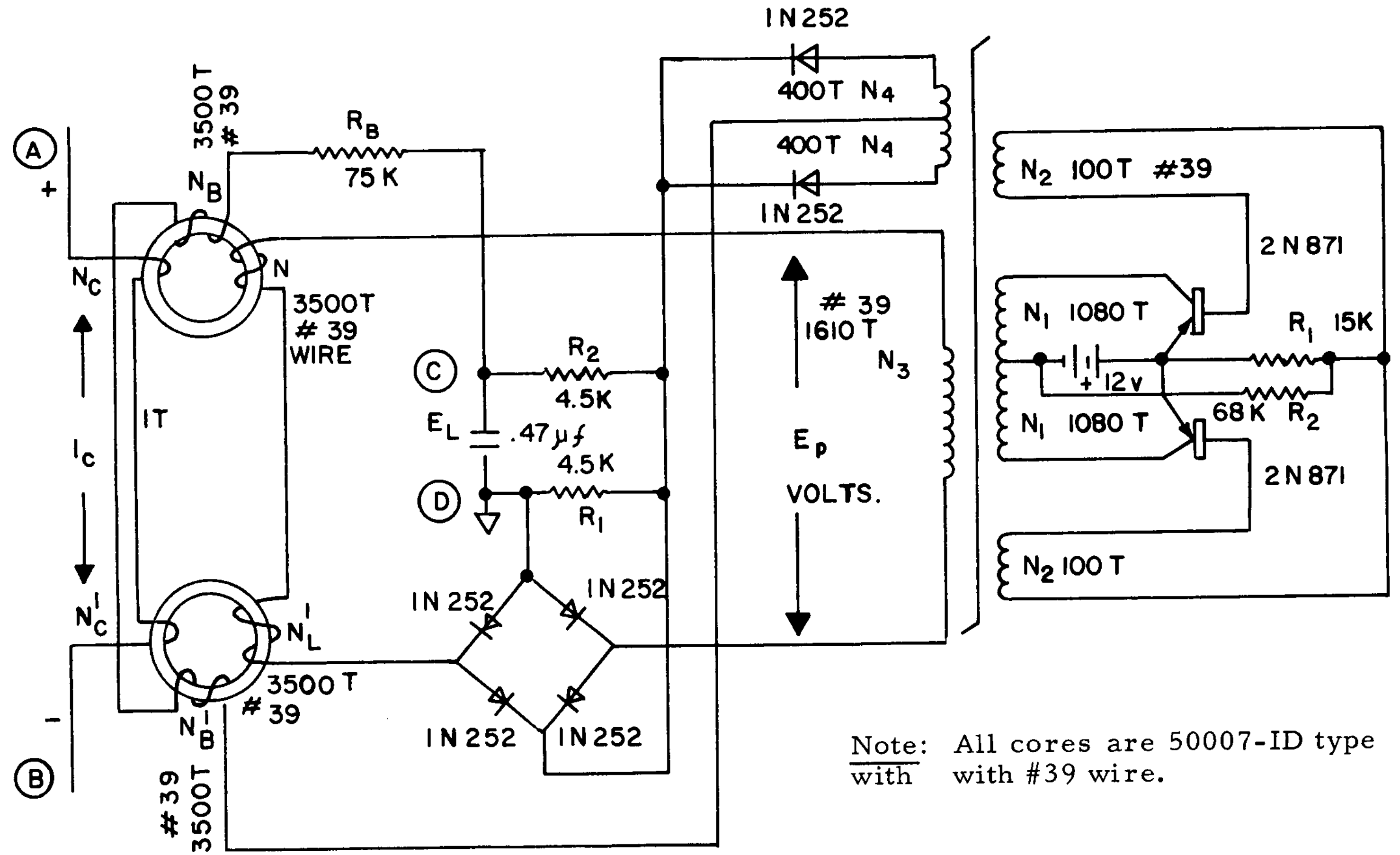
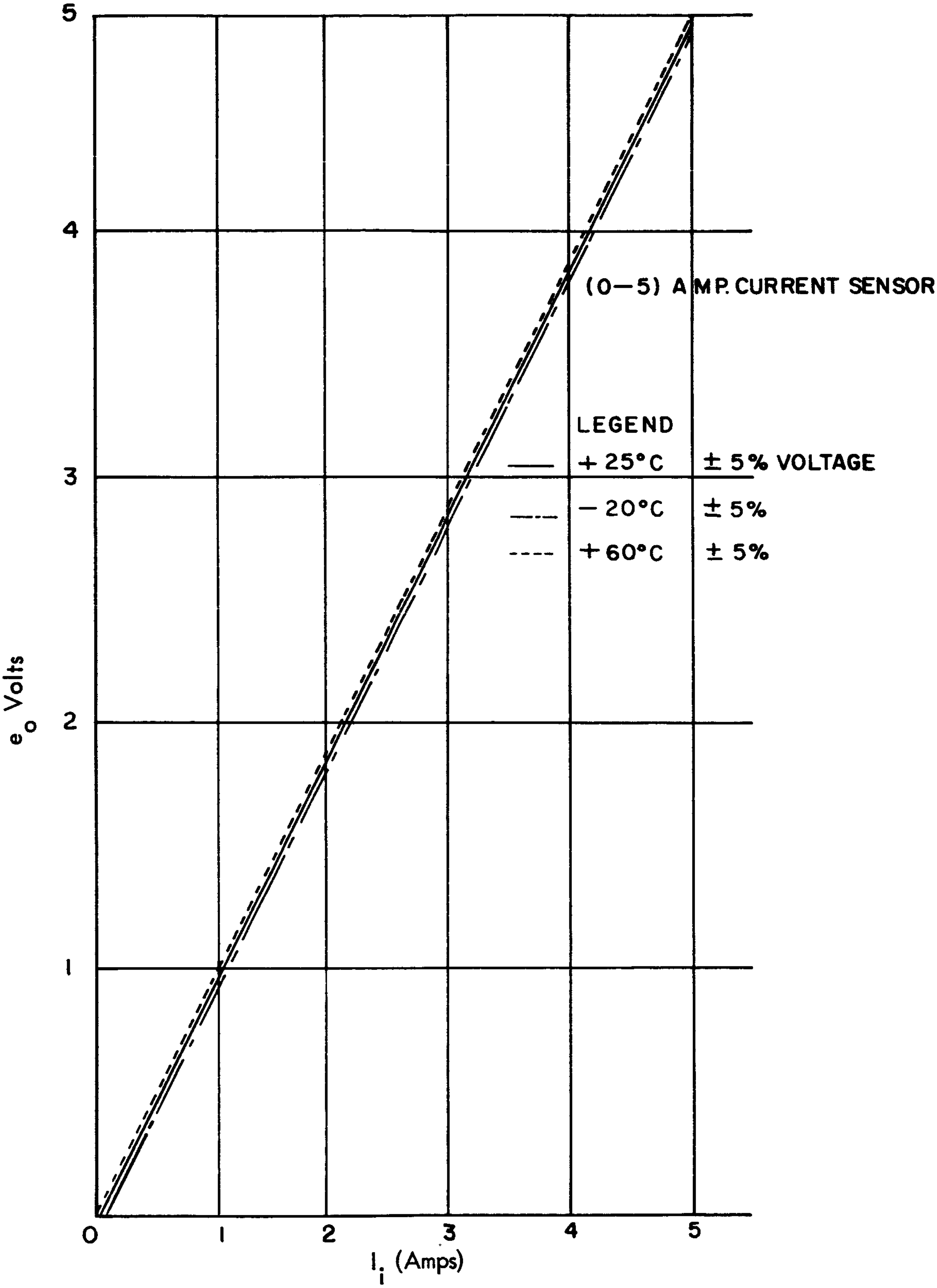



Figure 4. DC TO AC CONVERTER




Note: with All cores are 50007-ID type with #39 wire.

Figure 5. MAGNETIC AMPLIFIER AND DC TO AC CONVERTER CIRCUIT




Effects of Temperature on Output Voltage

Figure 6

## APPENDIX

### Power Supply Design

The design equations used to develop the circuit of Figure 4 are indicated below.

$$N_1 = \frac{E_1}{4B_m AF} \times 10^8 \qquad (8)$$

Where $E_1$ is the applied d-c voltage $B_m$ and A are flux density and effective cross-section of the core. F is frequency of operation. $N_2$ is determined from the transistor characteristics

$$I_b = \frac{I_L}{\beta} \qquad (9)$$

$N_2$ should supply at least one volt to the base of the transistor under all conditions.

$$N_2 = N_1 \frac{1}{E_1} \qquad (10)$$

The number of turns for $N_3$ is determined by the desired output voltage to the load thus:

$$N_3 = N_1 \frac{E_o}{E_1} \qquad (11)$$

The values for $R_1$ and $R_2$ are derived in the following manner:

$$E_{(N_2)} = \frac{N_2}{N_1} E_1 \qquad (12)$$

Then

$$R_1 = \frac{E_n 2}{\frac{N_3}{N_1} \frac{I_L}{\beta}} \tag{13}$$

and

$$R_2 = \frac{E^2 \quad \beta}{W \text{ (max)}}$$

where $\beta$ is transistor current gain W max. power rating of transistor operated class A. Further information on this subject can be obtained in Reference 3.

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